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# Training Metacognitive Skills for Problem Solving

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Metacognitive skills that involve monitoring and control of cognitive skills like problem solving develop in expert executives and lead to great improvement in the problem-solving process. In this report, we review theory and research on metacognition to construct a conceptual model that has three characteristics: (1) it shows the interrelationship of metacognitive skills and cognitive task performances, (2) it suggests the most valid assessment techniques for the measurement of metacognitive skills, and (3) it shows the development of metacognitive skills. From the third characteristic, we designed a training program to accelerate the acquisition of metacognitive skills in officers in the U.S. Armed Forces. From the second characteristic, we will construct proficiency tests of metacognitive skills for measuring these skills in commanders at various levels of professional development; the tests will also be used to evaluate the effectiveness of the training.

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TRAINING METACOGNITIVE SKILLS FOR PROBLEM SOLVING

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# TRAINING METACOGNITIVE SKILLS FOR PROBLEM SOLVING

High-level commanders and executives are expert problem solvers, but we understand very little of the nature of their expertise. We know that the executives have considerable knowledge and skill that enable them to perform their tasks in an expert manner, but we understand very little about the nature of this knowledge and these skills. The skills in particular are poorly conceptualized. We know they are not the kind of behavioral skills that psychologists have traditionally studied, such as riding a bicycle or shooting a rifle. Instead, these skills are "cognitive" skills; they involve manipulation and use of the elements of domain knowledge for some purpose, to some end.

A skill is defined as an ability to do something well, and a cognitive skill is thus defined as an ability to perform a cognitive task well. A cognitive task is one in which successful performance depends primarily on the possession and skillful manipulation of information and knowledge; the product of a cognitive task is usually cognitive as well — an idea, a plan, a decision, a solution to a problem. In the domain of executive performance by Army commanders, problem solving may be considered the generic cognitive task, encompassing the formal mission-planning tasks and the less-clearly defined decision-making tasks of Army command and control.

In addition to cognitive skills, executives seem to possess even higher-level skills that enable them to **use** their cognitive skills effectively. Called "metacognitive" skills, these are defined as abilities **to monitor and direct** the operation of cognitive skills to obtain the greatest possible success. Consider the example of what is perhaps the greatest cognitive skill of humans, the ability to construct sentences to convey meaning (that is, language). Metacognitive skills in the language domain include the use of one's knowledge of grammar or the lexicon to form more effective sentences, monitoring the response of the listener to diagnose communication success, and knowing when a picture is worth a thousand words.

## THEORIES OF METACOGNITIVE SKILLS

**Piaget's stages of intellectual development.** Jean Piaget has a theory of intellectual development that can be extended to the adult years. Infants are said to be at a relatively primitive, sensory-motor stage of intellectual development that, with the onset of speech, becomes a conceptual-symbolic stage called preoperational (Flavell, 1963). Around the age of six, children enter the stage of concrete operations, in which they can apply operations (mental routines) to transform information in some way — adding two numbers to get a third, placing all red objects in the same pile. Around the age of 12, children begin the final stage of intellectual development called formal operations, in which they can apply mental routines to abstract material. For example, an adolescent can solve a problem like "If a suitcase can eat four rocks in one day, how many can it eat in two days?" Younger children cannot imagine a suitcase that eats rocks, so they will refuse to answer the question; they cannot disregard the content of the problem (its concrete aspects) and reason in a purely hypothetical way (using the form, or formal aspects, of the problem).

The advent of formal reasoning creates an interest in form, that is, adolescents become fascinated by the formal structures and processes of thought. They think about thinking, which is a good definition of metacognition. One of the products of

Piaget's theory is a body of research on metacognition, much of it on memory or "metamemory"; this research will be discussed below.

**Metamemory.** Piaget's theory led to research on metacognitive skills in memory, or *metamemory*. The specific topic in which we are most interested is problem solving or what we might call *meta-reasoning*. Nevertheless, the research on metamemory is of interest, not only because it represents a productive approach to metacognitive skills, but also because it has been a developmental approach, which offers clues to the development of metacognitive skills in general.

John Flavell distinguishes between two broad areas of metamemory skills (Flavell & Wellman, 1977). The first is sensitivity to the need for planful memory. At first, the need for planful memory may be explicitly stated by a teacher or parent, who may instruct the child to remember something. Later the child may apply the metamemory skills spontaneously, knowing by now that one can prepare for later retrieval, that there is a difference between information processing for later recall and other cognitive processing of information. The second broad area of metamemory is knowledge of variables that affect memory performance. These variables include person variables (some people have better memories; people are likely to forget information learned under emotional stress), task variables (meaningless information is harder to remember), and strategy variables (rehearsal is a good mnemonic strategy). For example, children learn that if one variable, say task difficulty, is high, predicting poor memory, they must compensate with another variable, allocating more study time. The child may test memory and then concentrate rehearsal on the unlearned items.

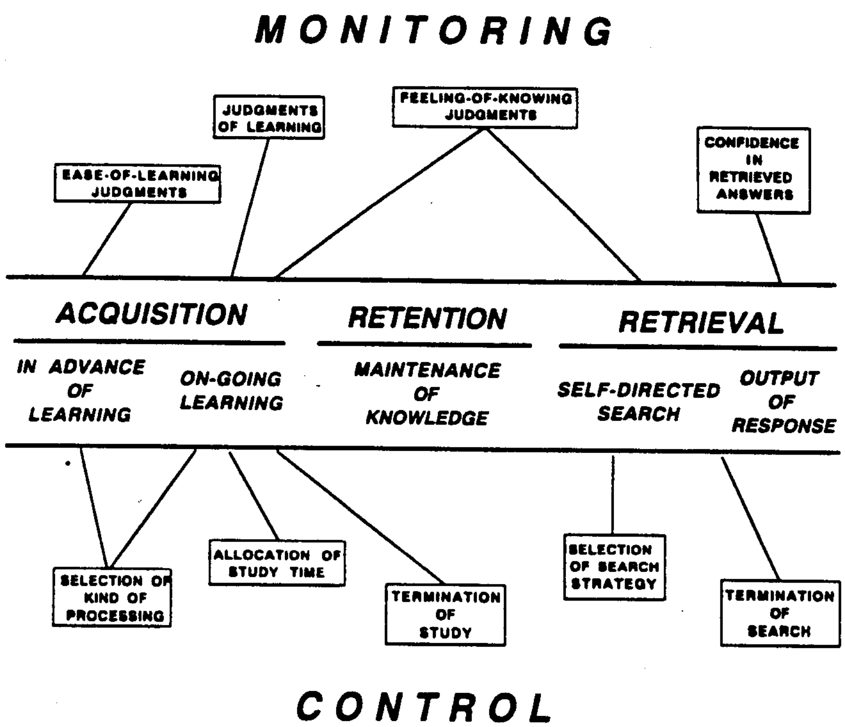



*Figure 1.* A theory of metamemory. (From Nelson & Narens, 1994)

Nelson's theory of metamemory, although limited to one kind of cognition, is another framework for our analysis (Nelson & Narens, 1990; 1994). Figure 1 depicts the stages of memory — acquisition, retention, and retrieval — and gives examples of both the monitoring and control functions of metamemory skills. The monitoring functions determine the control functions to be activated. For example, suppose people are asked to learn some material to a certain criterion — "Learn this list of CIA agents perfectly, then destroy the list" — and monitor list acquisition until they make a metacognitive "judgment of learning" (JOL) or experience a "feeling of knowing" (FOK). If the JOL and FOK indicate that more study is required, control functions are activated; the kind of learning strategy is selected (rote memorization, use of mnemonic devices), and study time is allocated to the individual items on the list, according to the metacognitively perceived need. In a retrieval task, FOK and one's confidence in retrieved answers (CRA) determines search strategy and, ultimately, termination of the search.

**Adult stages of metacognitive development.** Piaget's stages have been extended to the adult years by Schaie and Geiwitz (1982). The development of formal operations suggests that metacognitive structures and strategies can be applied to direct cognition toward problem solution, a skill that continues to develop throughout adulthood. The adult stages of intellectual development reflect a general increase in metacognitive skills, which underlie adult application and use of knowledge, rather than increases in cognitive skills, which underlie childhood acquisition of basic knowledge. The first adult stage, which occurs in young adulthood, is **temporal monitoring,** which represents the application of intelligence in situations that have profound consequences for achieving long-term-goals (involving decisions about career and marriage). Temporal monitoring is a kind of quality control process applied to problem-solving when the solutions must be integrated into a life plan that extends far into the future. It is similar to skills used by Army commanders when they prepare a synchronization matrix for the various Battlefield Operating Systems in a mission plan.

A second major application of intellect in adulthood occurs in the second adult stage, called **social monitoring.** Typically this stage develops when a family is established, and the individual must begin monitoring not only his or her own behavior, but also that of spouse and offspring. Similar extensions of monitoring skills are required, as responsibilities for others are acquired on the job and in the community. Social monitoring includes temporal monitoring of a group of people who are all working toward the same end; not only must their activities be synchronized for maximum effectiveness, but metacognitive skills such as resource allocation and the efficient division of labor among group members become primary determinants of group performance. In Gardner's theory of multiple talents, social-monitoring skills fall into the category of personal intelligence (Gardner, 1983), which includes the ability to take another person's perspective in a training situation; Anne Sullivan, the teacher of Helen Keller, is assumed to have been high in personal-social intelligence and skills. In the military domain, social monitoring is a set of metacognitive skills that will serve a commander of a combined-arms unit well.

A third adult stage of intellectual development we call **executive monitoring.** Many individuals' responsibilities become exceedingly complex. They become presidents of business firms, deans of academic institutions, officials of churches, or

commanders of divisions or corps. As such, they need to understand how an *organization* works: the structure and the dynamic forces, who answers to whom, and for what purpose. They must monitor organizational activities not only on a temporal dimension (past, present, and future) but also up and down the hierarchy that defines the organization. Executive monitors must know the plans and intentions of superiors, and they must devise a structure for monitoring and controlling the implementation of policies at the lower levels of responsibility.

**Metacomponents of intelligence.** The role of metacognition in problem solving has been investigated by Sternberg (1984, 1985) in support of his triarchic theory of intelligence. Sternberg has focused on the executive-process aspect of metacognitive skills, that is, the ability to organize, sequence, and monitor cognitive processes for maximum effectiveness. In the componential subtheory, three types of components (intellectual processes) are defined, one of which is *metacomponents.* "Metacomponents are higher-order executive processes used in planning, monitoring, and evaluating one's problem solving" (Sternberg, 1988, p. 132). In Sternberg's (1985) early writing, he listed seven prominent metacomponents:

1. deciding just what the problem is
2. selecting lower-order components to solve the problem
3. selecting information representations
4. selecting strategies for combining lower-order components
5. deciding how to allocate attentional resources
6. monitoring the solution: what has been done, what is being done, what still needs to be done
7. monitoring feedback: altering behavior on basis of feedback: "How am I doing?"

In later works, Sternberg has focused on four metacognitive skills that are valuable in problem-solving tasks (Davidson, Deuser, & Sternberg, 1994). These are 1) Identifying and Defining the Problem, that is, how to recognize that there is a problem to be solve; 2) Representing the Problem, that is, how to figure out what exactly the problem is; 3) Planning How to Proceed, which, together with 4) Evaluating Your Performance, helps you to understand how to reach a solution. These are relatively well-documented metacognitive skills that we will return to, in later sections, since they appear to have good construct validity and, when applied in a problem-solving task, promise significant benefit.

With this sampling of theoretical approaches to metacognition, we turn now to a sampling of research results. This research provides data relevant to the value of metacognitive skills: Do they make a difference in performance in problem-solving tasks? In some studies, another question addressed is how the metacognitive skills are trained and assessed.

## METACOGNITIVE SKILLS AND PROBLEM-SOLVING PERFORMANCE

There is not a large literature on training metacognitive skills and then evaluating the benefits on problem-solving performance. In general, the more

common study seeks to determine if good problem solvers have more existing metacognitive skills than poor problem solvers. In general, the good problem solvers do have more of these skills, both as children and adults (Metcalfe & Shimamura, 1994). In the domain of electronic trouble shooting, the most proficient technicians used more complex and more accurate mental models than the less competent electricians (Gitomer, 1988). More complex and more accurate mental models were also used by successful subjects in another study of troubleshooting abilities, in computer hardware problems; these subjects also used strategies to focus data-gathering activities (Reed & Johnson, 1993).

I have personally developed hundreds of task-based proficiency tests for mechanics, electricians, and instrument/control technicians in the nuclear power industry. We discovered that, especially in the diagnostic tasks, the proficient technicians were those who had metacognitive skills to guide their investigations and, therefore, we had to assess these skills in our proficiency tests (Geiwitz, Spiker, & Harris, 1988; Spiker & Geiwitz, 1989). We then revised the training program for a subgroup of these technicians involved in ultrasonic testing of pipes for cracks. The good inspectors, we had learned, were those that developed a strategy of hypothesis testing when they recording a suspicious signal. They maneuvered their instruments to gather data relevant to competing hypotheses of crack vs. no_crack, or as is common in power plants, crack vs. weld_seam. So we inserted a one-hour segment on hypothesis testing into the 40-hour nuclear-power NDE (nondestructive evaluation) training courses. By this change, in 1 of 40 training hours, we were able to increase the frequency of successful detections by over 30% (Harris, 1992). This is a remarkable excess of benefit over cost that shows the promise of training personnel in metacognitive skills. In certain cases, it can result in an astounding increase in problem-solving performance.

Nisbett's work on teaching reasoning is directly relevant to our project (Nisbett, Fong, Lehman, and Cheng, 1987). Psychology has shown that formal, deductive logic cannot be taught; it has also shown that humans rarely use formal logic in reasoning. What they do use in reasoning -- mental models, causal schemas, and statistical heuristics -- is effective and can be taught. For example, educated laypeople use an intuitive version of the law of large numbers as a heuristic to aid them in reasoning about probabilistic events with uncertainties. The heuristic is, roughly, "Larger samples are required when generalizing about populations that are more variable than average." Thus, more observations of a baseball hitter are required to estimate his batting ability than of a neurosurgeon, whose surgical performances are less variable. These heuristics can be taught to others, as can similarly useful mental models and schemas. The interesting discovery of Nisbett's group, from our point of view, was that these metacognitive skills (using models strategically) cannot be trained by knowledge transfer alone, that is, the subjects must be given practical examples to solve using the skills; without repeated practice, no training benefit ensues. In our terms, Nisbett is teaching the procedural knowledge (the how to knowledge) along with the semantic knowledge (understanding the principles and heuristics). The procedural knowledge is crucial for training. We encountered a similar need for procedure-training when we tried to develop a course to teach supervisors how to construct performance tests of mechanical and electrical skills. The supervisors soaked up test theory with ease and could repeat it flawlessly, if queried. But they

could not use the theory to actually construct tests until we taught them the step-by-step procedures for applying principles to real life situations (Geiwitz, 1992).

## TRAINING METACOGNITIVE SKILLS: A CASE STUDY

In a most impressive implementation of a training program for metacognitive skills, Reif, Larkin, and their associates have developed training modules for science education, modules that emphasize and teach the metacognitive skills required for problem solving in college physics (Reif & Larkin, 1991). Their research began with an assessment of current educational difficulties. To summarize a considerable body of research, college physics students seem to "know" the concepts of physics, such as velocity and acceleration, but they cannot use this knowledge to solve even simple problems in that domain. For example, Heller and Reif (1984) found that Berkeley students (who had completed a basic physics course with a grade of B or better) could solve correctly only about 35% of typical textbook physics problems of the kind repeatedly encountered in their course. Other studies revealed that students' problem-solving *methods* were primitive and inadequate to the task (Larkin, 1982).

### KNOWLEDGE BASE AND PROBLEM-SOLVING STRATEGY

Using a cognitive science approach, Reif and Larkin constructed instructional interventions for students' difficulties in scientific problem solving. They tried to identify the declarative and procedural knowledge required, especially the procedural, often the source of difficulty. The students did not know (were not taught) *how* to apply the concepts they had learned. Although most of the interventions were empirically based on experiments, theoretically the interventions turned out to be, in essence, training of metacognitive skills. For example, students were taught how to describe a problem so that the representation facilitates a solution (Heller & Reif, 1984). They were encouraged to formulate plans and strategies for problem solving. They were taught to recognize errors, especially when concepts had both an everyday and a scientific definition, with subtle differences that could lead to errors — "acceleration" is an example. Specific methods of concept application were also included in the metacognitive curriculum. In sum, the students were taught the *process* of problem solving: how to make judicious decisions, select appropriate methods, avoid dead ends, and recover from mistakes.

The Reif-Larkin model for scientific problem solving consists of a problem-solving strategy together with a knowledge base, which provides the scientific information in the relevant domain (currently physics, specifically mechanics). The knowledge base is organized hierarchically, with central ideas described qualitatively at the highest level of the network and quantitative elaborations at lower levels. The principles in the knowledge base are accompanied by auxiliary information specifying when they are valid and/or likely to be useful.

The problem-solving strategy is based on studies of expert problem solvers (Larkin, 1982) and on the strategies that worked in pilot implementation among college physics students (Heller & Reif, 1982). Like the knowledge base, the strategy is organized hierarchically. At the highest level, the strategy defines three

subprocesses: describing the problem, constructing a solution, and checking the solution. (Problem description is one of our metacognitive skills, and, as we shall see, the skills involved in the other two subprocesses are also largely metacognitive.)

Lower in the hierarchical network, the main subprocesses are further decomposed. Problem description is decomposed into "problem summary" and "technical description." The problem summary is a summary of available information about the situation, including the goal of the problem-solving endeavor. The technical description redescribes the problem in terms of properties of, and interactions among, the objects by using the relevant portions of the knowledge base. Its purpose is to facilitate application of the knowledge base to construct a solution. In mechanics, the technical description had two stages: 1) an interaction description, which uses a diagram (often from the problem summary) to identify all the interactions between systems; and 2) a system description, a diagram for each system of interest. Each diagram describes the motion of the system (in terms of position, velocity, and acceleration) and the interactions of this system (in terms of forces upon it). The diagrams also allow internal checks, e.g., the consistency between acceleration and total force. Arrows indicate vector quantities and direction, and equations indicate information about magnitudes.

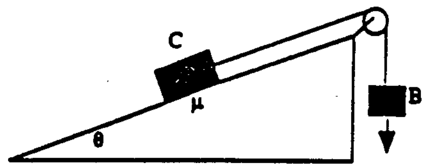
The second main subprocess, constructing a solution, involves decomposing the original problem into subproblems, each of which are solved in turn, ultimately leading to a solution of the original problem. Each solution requires the identification of alternatives and the judicious choice of one of these alternatives. Alternatives are explicitly stated in the knowledge base and strategy. Choice is based on an estimate of the utility of the consequences of that choice; if the choice proves unsatisfactory, one can backtrack to select one of the other alternatives.

The actual construction of a solution specifies two complementary methods. The first method is to apply a central principle from the knowledge base (e.g., a law of mechanics) to a system in the problem with a convenient description (e.g., along a particular direction, if vectors are involved). This method simplifies a potentially complex choice by specifying three sets of concepts — a principle, a system, and a description — each of which provides only a small number of possible options, as suggested by the knowledge base and technical description. The second method involves removing unknown quantities in the relationships developed in the first method, by combining relationships (algebraically combining formulas to eliminate unknowns). The two methods can be reapplied as many times as necessary, until the problem is solved.

The third main subprocess is an evaluation of the solution, to determine if it is clear, correct, and otherwise satisfactory. One of the primary checks is consistency, that is, the solution must be consistent with other known facts about the system in question, including the general principles of mechanics that apply to its behavior. Common mistakes can also be evaluated, to see if their influence in this particular solution has been substantial or negligible.

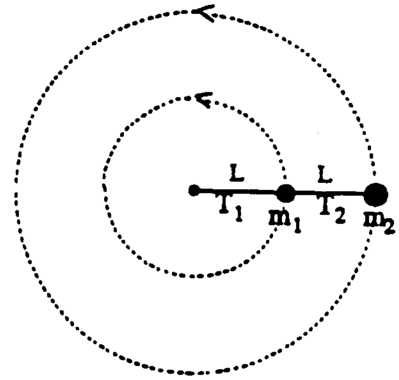
## TRAINING PHYSICS STUDENTS

In 1992, Reif and Larkin (1993) taught a section of the introductory physics course at Carnegie-Mellon University, with 56 randomly selected students. Other students took the regularly-offered course. On four common questions in the final exams of the two groups, the experimental section performed at a significantly higher level than the conventional section; see Figure 2. On the inclined plane problem (top left), 70 percent of the experimental students made no errors (or made only minor arithmetic errors); the regular students made major errors in all but 10 percent of observations! On other questions, the regular students fared somewhat better, but the experimental students retained their substantial edge. In addition to greater success in problem solving, the experimental students did not make the mistakes common in the conventional classroom, and they did not persist in erroneous reasoning as the conventional students did. In sum, the metacognitive skills training program was a big success. (Carnegie Mellon University asked Reif and Larkin to take over all of the introductory physics course, which they have done; they have lost their control group, but the size of the experimental group will allow more fine-grained statistical analysis.)




Tension force T by string = ?

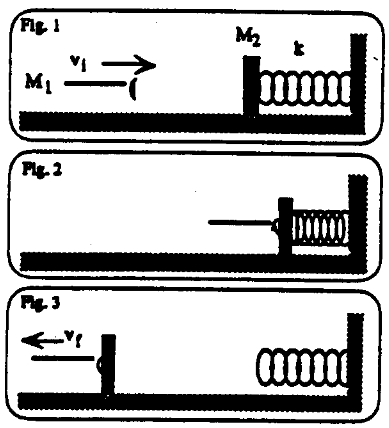
| Errors | Regular | Special |
|---|---|---|
| None or minor | 10% | 70% |
| $T = W_B$ | 35% | 7% |
| $\Sigma F = 0$, $a = g$, ... | 37% | 7% |




Tension forces by the strings

$T_2 = ?$ $T_1/T_2 = ?$

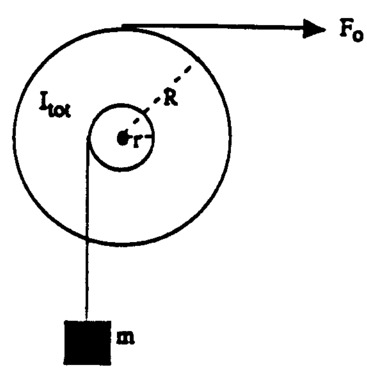
| | Regular | Special |
|---|---|---|
| $T_2$ | 27% | 70% |
| $T_1/T_2$ | 10% | 30% |




Max. compression = ?

Accel at that instant = ?

| | Regular | Special |
|---|---|---|
| Compression | 20% | 48% |
| Acceleration | 57% | 85% |




Angular acceleration $\alpha = ?$

At rest, $F_o = ?$

| | Regular | Special |
|---|---|---|
| $\alpha$ | 0% | 31% |
| $F_o$ at rest | 37% | 69% |

*Figure 2.* Percentage of students in regular and special sections who answered correctly the four questions on the final examination.

## STRUCTURE AND CONTENT OF THE METACOGNITIVE TRAINING

The basic structure of the Reif-Larkin approach has been described above and is summarized in Table 1.

Table 1
Components of the Reif-Larkin Training for
Enhanced Problem-Solving Performance

| | |
|---|---|
| KNOWLEDGE BASE | • concepts and principles<br>• "operational" definitions<br>• organized hierarchically<br>• describes when principles to be applied |
| PROBLEM-SOLVING STRATEGY: problem description | • qualitative problem summary<br>• technical (theoretical) description |
| PROBLEM-SOLVING STRATEGY: construction of solution | • decomposition into subproblems<br>• application of relevant knowledge<br>• application of relevant quantitative formulas |
| PROBLEM-SOLVING STRATEGY: evaluation of solution | • consistency<br>• common mistakes |

### Knowledge Base

To illustrate the design of the domain knowledge base, I will describe the definitions and interpretations of the concept of acceleration contained in the textbook (Reif, 1993a). Acceleration is defined in Chapter 4 on Velocity and Acceleration, where motion is discussed in terms of the change of position of an object over time. After the discussion of velocity, acceleration, like all important new concepts, is introduced qualitatively, as a means of describing how rapidly the velocity of an object changes. This change may be in the magnitude of the velocity (the common sense definition of acceleration), but it may also be in the direction of the velocity, with no change in magnitude. Thus, "if a car travels along a curved road with constant speed, its velocity ... changes because the direction of its velocity changes" (Reif, 1993a, p. 31). This description is supported by vector diagrams, as shown in Figure 3.

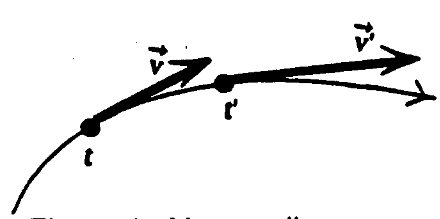


*Figure 3.* Vector diagram.

To describe the rapidity with which velocity changes, the concept of *average acceleration* is defined as the change in velocity between time 1 and time 2 divided by the change in time (t2-t1). Average acceleration is easy to understand, but it is not very useful, because velocity can change in several different ways within a lengthy time interval. What we want is a very short time interval or, more precisely, we want to define *acceleration at an instant:* a = dv/dt, in simple terms of the calculus.

Reif then presents the "defining method," that is, the things one must observe and/or do to identify acceleration in a particular case, as shown in Figure 4. The defining method is the "operational definition" of the concept. This definition is then supplemented with other knowledge about the concept, including the situations or conditions in which the definition is valid, the vector properties of the concept, warnings about common errors in interpretation, the units of acceleration, and what is required for a complete specification of the concept.

***Finding acceleration*** $(\vec{a} = d\vec{v}/dt)$

(1) ***Original velocity*** $\vec{v}$. Identify the velocity of the particle at the time t of interest.

(2) ***New velocity*** $\vec{v}'$. Identify the velocity of the particle at an infinitesimally later time t'.

(3) ***Change of velocity*** $d\vec{v}$. Find the velocity change $d\vec{v} = \vec{v}' - \vec{v}$ of the particle during the infinitesimal time interval dt = t' - t.

(4) ***Acceleration*** $\vec{a}$. Find the ratio $\vec{a} = d\vec{v}/dt$. [This is the "acceleration of the particle at the time t" *if* dt is infinitesimally small.]

(5) ***Check.*** Check that the time t' has been chosen sufficiently close to t (i.e., that dt is sufficiently small) that the value obtained for the acceleration would be unaffected by a closer choice. If this is not the case, repeat the method with a time t' chosen closer to t.

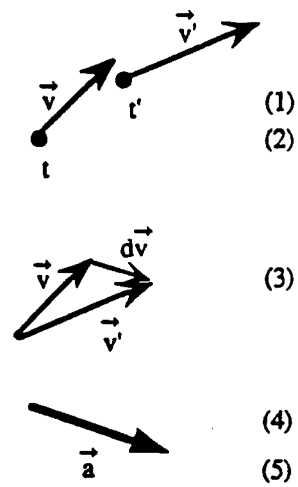



*Figure 4.* Defining method for interpreting the concept of acceleration.

## PROBLEM-SOLVING STRATEGIES

To teach the problem-solving strategies, Reif (1993b) constructed a workbook, which is described in the textbook as "the primary learning aid." The workbook is designed to actively engage the student in interpreting and applying newly acquired knowledge. Whereas the textbook contains declarative knowledge, the workbook contains the critical procedural knowledge — what one actually *does* to interpret a concept in a particular instance.

**Problem description.** How one describes the problem, as we have often suggested, is half the battle; Reif and Larkin teach an explicit method for describing any problem so as to facilitate a solution. The method involves two stages: 1) a basic problem description that clearly specifies the problem situation and goals; and 2) a more theoretical description in terms of relevant concepts and principles. The first stage translates the problem as found into a diagram of objects and their relationships, with useful symbols, time sequences, and other relevant information. The goal state of the problem-solving endeavor is also stated clearly and explicitly.

In the second stage of problem description, concepts and principles from the knowledge base (textbook) are used to describe the mass of objects, the motion of objects, and especially all forces on the system of interest. Heller and Reif (1984)

specify an explicit procedure for generating this theoretical description, a procedure comprising the following steps:

1) identification of the particular entities that should be described

2) application of special concepts from the knowledge base to describe these entities

3) exploitation of particular properties of these concepts

4) application of particular principles from the knowledge base to check that the description is self-consistent and correct

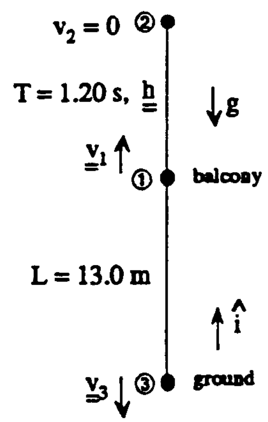
In physics, specifically in mechanics, the "particular entities that should be described" (step 1) are particles or systems of many particles. Particles or systems relevant to the problem are those about which information is desired and those that interact with such entities. The "special concepts" (step 2) are of two kinds. One, used to describe individual particles, includes concepts to describe the intrinsic characteristics of particles (e.g., mass) and other concepts to describe the motion of particles (e.g., acceleration). The second kind of concept is used to describe the interaction between particles (e.g., force). One should draw a motion diagram, describing the position, velocity, and acceleration of the relevant particles, and a force diagram, describing the external forces on the particles. The important properties of the special concepts (step 3) include various interaction laws that specify how the concepts describing interactions are related to the concepts describing motion, for example, how forces are related to acceleration. Some of these interactions are short-range, that is, they are substantial only when interacting particles are touching, and others (like gravity) may be substantial even with particles separated by some distance. In practice, step 3 prescribes the evaluation of forces exerted by *each object that touches the relevant system*, plus the long-range force of gravity (interaction of the earth with the relevant system). Finally, the knowledge base includes "motion principles" that specify how the motion of particles changes as a result of interactions among them (e.g., F = ma, which relates the acceleration of a particle to the sum of forces exerted on it). This principle should be used to check the descriptions of motion and interaction (step 4); for example, the acceleration of each particle must have the same direction as the total force on it. Step 4 cannot simply direct the student to ensure that motion and interaction descriptions are consistent with a specified principle. It is necessary also to indicate *how* one can determine such consistency. (The specific instructions for each step are contained in Appendix A.)

When this procedure was used in an experiment, physics-student subjects solved an average of 2.75 difficult problems out of 3.00, compared to 0.63 for control subjects who had had relevant physics courses but who were given no guidance (Heller & Reif, 1984). Several of the experimental-group subjects were surprised at the efficacy of the procedure, stating with some amazement that the problems suddenly became very easy to solve!

**Solution construction.** The strategy that Reif and Larkin teach to construct a solution to the problem is essentially "divide and conquer." The problem is divided

into a series of subproblems, each of which is conquered in turn, until the problem as a whole is solved. In most cases, two stages exist for solving the subproblem: 1) application of a principle (here, a mechanics law) to the system under consideration, and 2) eliminating unknown and unwanted quantities from the relations specified in step 1, by algebra. Figure 5 shows a skilled description of a problem, and Figure 6 shows the three-part solution. The solution depends upon the application of three basic relationships describing motion with constant acceleration:

- relation (velocity, time): $v_x - v_{xo} = a_x t$
- relation (displacement, time): $D_x = v_{xo}t + 1/2\, a_x t^2$
- relation (velocity, displacement): $v_x^2 - v_{xo}^2 = 2a_x D_x$




①→② = T = 1.20 s

①→③: $a_x = -g$

Known: T, L

Goals: (a) $v_1$ = ?

(b) h = ?

(c) $v_3$ = ?

Situation diagram with time sequence indicated by successive important instants ①, ②, ③, ....[①→② indicates the time elapsed between instants ① and ②.]

①: Ball leaves hand with speed $v_1$.
②: Ball at highest point, height h.
③: Ball at ground, distance L below hand.

The ball's acceleration is equal to $\vec{g}$ during the entire time ①→③. There is thus only one distinct time interval.

Velocity at highest point is zero since height there momentarily neither increases nor decreases, i.e., does not change.

Wanted unknown quantities are doubly underlined in the diagram.

*Figure 5.* How to describe a problem.

(a) (Find $v_1$.) Rel(vel, t), ①→②, up

*Need to relate velocities and known time T. Hence apply rel(vel,t).*

$$v_x - v_{xo} = a_x t$$

$$0 - \underline{\underline{v_1}} = -gT$$

*Motion described relative to upward $\hat{i}$ direction.*

$$\boxed{v_1 = gT} \qquad (1)$$

*Result in terms of symbols.*

$$v_1 = (9.80\ \mathrm{m/s^2})\ (1.2\ \mathrm{s})$$

$$\boxed{v_1 = 11.8\ \mathrm{m/s}} \qquad (2)$$

*Numerical result.*

(b) (Find h.) Rel(disp, t), ①→②, up

*Need to relate upward displacement h to the known elapsed time T. Hence apply rel(disp, t).*

$$D_x = v_{xo}t + \frac{1}{2}a_x t^2$$

$$\underline{\underline{h}} = v_1 T - \frac{1}{2}gT^2 = (gT)T - \frac{1}{2}gT^2$$

By (1):

$$\boxed{h = \frac{1}{2}gT^2} \qquad (3)$$

*Result in terms of symbols.*

$$h = \frac{1}{2}(9.80\ \mathrm{m/s^2})\ (1.2\mathrm{s})^2$$

$$\boxed{h = 7.1\ \mathrm{m}} \qquad (4)$$

*Numerical result.*

(c) (Find $v_3$.) Rel(vel, disp), ①→③, down

*Need to relate velocities to displacement, without being interested in required time. Hence apply rel(vel, disp).*

$$v_x{}^2 - v_{xo}{}^2 = 2a_x D_x$$

$$v_3{}^2 - v_1{}^2 = 2\,g\,L$$

*Since we have decided to measure quantities downward, $a_x = +g$ and $D_x = +L$.*

$$\boxed{v_3 = \sqrt{v_1{}^2 + 2gL}} \qquad (5)$$

$$v_3 = \sqrt{(11.8\ \mathrm{m/s})^2 + 2\ (9.80\ \mathrm{m/s^2})\ (13.0\ \mathrm{m})}$$

$$\boxed{v_3 = 19.9\ \mathrm{m/s}} \qquad (6)$$

*Figure 6.* How to construct a solution.

The construction of a solution is less well specified by Reif and Larkin than other aspects of problem solving, e.g., problem description. Instead of a detailed procedure, Reif and Larkin describe the general procedure, as above, and rely on numerous examples, to be worked out by the student using the general procedure. Nevertheless, the details of the solution-construction process need more careful description, if metacognitive skills are to be trained effectively.

**Solution evaluation.** "The initial solution of a problem is rarely free of errors or other deficiencies. Hence any solution must be regarded as provisional until it has been checked and improved" (Reif, 1993a, p. 59). Reif presents the following questions, "useful to detect deficiencies in the solutions":

- Have the **goals** of the problem-solving task been **attained**? (Has all wanted information been found?)
- Is the solution **well-specified**?
  - -- Are answers expressed in terms of known quantities?
  - -- Are units specified?
  - -- Are both magnitudes and directions of vectors specified?
- Is the solution **self-consistent**?
  - -- Are units in equations consistent?
  - -- Are signs (or directions) on both sides of an equation consistent?
- Is the solution **consistent** with **other** information outside the problem?
  - -- Are values sensible (e.g., consistent with known magnitudes)?
  - -- Are answers consistent with special cases (e.g., extreme or simple cases)?
  - -- Are answers consistent with known dependencies (e.g., with knowledge of how quantities increase or decrease)?
  - -- Are answers consistent with those obtained by other solution methods?
- Is the solution **optimal**?
  - -- Are answers and solution as clear and simple as possible?
  - -- Is the answer a general algebraic expression rather than a mere number?

Like the construction of the solution, the solution check is phrased in general terms that make little sense to the students until they have worked through numerous examples. While practice is not a bad way to train these metacognitive skills, more detail should be given at some point, perhaps following the practice.

The Reif and Larkin program is encouraging to those of us trying to develop training methods in other domains. As we have seen, metacognitive skills seem to enhance problem-solving performance, often to an unexpectedly high level. Nisbett, Reif, and others have shown us that these skills can be taught. We turn now to the question of which skills should be taught? Which metacognitive skills are most important for problem solving?

## METACOGNITIVE SKILLS

Metacognitive skills are defined as abilities **to monitor and direct** the operation of cognitive skills to obtain the greatest possible success. A cognitive skill, in turn, is defined as the manipulation and use of the elements of domain knowledge for some purpose, to some end. In short, a cognitive skill enhances the performance

of a cognitive task. In the domain of executive performance by Army commanders, **problem solving** may be considered the generic cognitive task, encompassing the formal mission-planning tasks and the less-clearly defined decision-making tasks of Army command and control.

Here, from various sources and insights, is a list of ten metacognitive skills that have shown promise as candidates for training, if enhanced problem solving is our goal:

**Detection of a problem.** Recognizing the existence of a problem sounds easy enough, but in fact it is a skill that varies considerably among people, and it is highly correlated with intelligence and creativity (Sternberg, 1988). Somehow the individual must monitor the discrepancies between the current state and the goal state, noting a problem when the discrepancies exceed a certain value. Intelligent problem-solvers not only recognize that a problem exists, they are also better at identifying the critical problems in a domain; in the words of one researcher, they have "good taste" in problems (Zuckerman, 1983).

**Representation of a problem.** Once expert problem solvers have recognized the problem, they define the problem in a way that makes the problem soluble (Sternberg, 1988). They represent the problem mentally (or in a computer program) in a form that is close to optimal for problem solution. This is an extremely valuable skill, perhaps the single most valuable of the metacognitive skills: How an individual states the problem is a prime determinant of success in solving it.

**Selection of a problem-solving method.** There are many ways to solve problems. Good problem solvers know many methods, and they have the ability to select wisely, choosing appropriate procedures for solving the particular problems of the specific domain.

**Strategic application of problem-solving methods.** Good problem solvers have strategies for solving the problem. They apply a potentially effective method, constantly monitoring the changes in problem state that the method produces to see if a solution has occurred. They know what they will try next, and why. Strategies and methods in problem solving have much the same relationship as strategies and tactics in command and control.

**Evaluation of solution candidates.** Like the wargame evaluation of the three Courses of Action selected in the mission-planning process, good problem solvers evaluate potential solutions, to see if the discrepancy between goal state and current state has been reduced.

**Recognition of errors.** Good problem solvers spot errors more quickly and more accurately than poor problem solvers. Common errors that result from cognitive biases and misapplied heuristics of the sort studied by Tversky and Kahneman (1974) are anticipated and guarded against.

**Resource allocation.** Good problem solvers, when they identify a problem, can allocate their problem-solving resources to create the most advantageous

environment for the solution to the problem. If the problem requires memory, for example, they know how long it will take to memorize the material, and they allocate the time accordingly.

**Temporal monitoring.** Temporal monitoring includes the effective and strategic allocation of time resources, but it also includes the monitoring function, to see if the solution is developing "according to schedule." Successful managers are noted for their ability to maximize the effective use of their time (Bray & Howard, 1981). In complex problems, many resources must be synchronized for maximum impact.

**Social monitoring.** Problem solving in a social context — that is, *most* problem solving — is different from the same activity in isolation. Good problem solvers allocate human resources wisely, and they try to establish a social environment in which the group can function effectively. This means, among other things, they have to take personalities into account, watch for conflicts, and moderate disputes. To manage effectively they must have sensitivity and understanding of other peoples' perspectives and goals.

The social-emotional aspects of leadership became more important in American businesses as big corporations changed from family-owned enterprises controlled by autocratic individuals to publicly owned corporations led by committees. Psychologists were brought in to advise corporations on how best to solve problems in groups (Geiwitz, 1980). It was soon discovered that lack of knowledge and logic was not the chief impediment to effective group solutions; interpersonal relationships were much more crucial. One member of a committee would suggest a perfectly logical solution to a problem, but the group would reject it, because they disliked him or her. Thus, the original groups of executives brought together to learn how to solve problems — called "training groups" or "T-groups" — were soon supplanted by "sensitivity T-groups" and, later, "encounter groups." Members of these groups learned how to recognize the emotional reactions their actions provoked in other people, usually through interaction and interpretation.

**Executive monitoring.** Executives have key positions in a hierarchical network of individuals. To be effective problem solvers, they must understand their position in the network: their relationship with higher authorities, their relationship with subordinates, their relationship with peers. Executive monitoring is more than temporal and social monitoring, although it includes these lesser skills. In one study, for example, the major difference between young executives and older, more experienced executives was the greater ability of the older executives to market for the company (Schaie & Geiwitz, 1982). Marketing is a very high level skill, involving knowledge of what the company is trying to do, good perception of the needs of a potential customer, and a good sense of the company capabilities to solves certain kinds of problems. It usually develops slowly over the lifespan, and many executives never become accomplished at business development.

## A CONCEPTUAL MODEL OF METACOGNITIVE SKILLS

To develop a model of how metacognitive skills augment and facilitate the cognitive skill of problem solving, we need first a model of the problem-solving task. Complete, theory-bound models of problem solving do not exist, but the general stages and principles have been described by many; the Command Estimate is based on such descriptions. Problems are "initial states," their solutions are "goal states," and problem solving methods are means for transforming the initial state into a goal state (Newell & Simon, 1972). Problem solving in the business world (therein called management) has been described by Kepner and Tregoe (1965) and Plunkett and Hale (1982) in similar terms. The Command Estimate is another general description of the problem solving process. After analysis of the mission and the orders, relevant information about the situation (including the terrain of the battlefield) and the enemy is collected, in effect identifying and describing the problem and the goal state (the mission objectives). A number of actions that might solve the problem are described — Courses of Actions (COAs). Each COA is played out, step by step, in a wargame technique and evaluated in terms of several mission objectives. One COA is recommended, but all are briefed to the commander, who makes the final decision. The Command Estimate, therefore, describes in more detail Step 4 above, suggesting that the problem solver generate options, evaluate these options, and then choose the option with the greatest apparent likelihood of success. These skills, however, may be better considered metacognitive.

### TECHNICAL MONITORING AND CONTROL

Our conceptual model of metacognitive skills focuses on those skills that facilitate the technical activities in problem solving. The technical aspects of problem solving comprise the purely formal operations designed to identify, represent. and solve the problem. In addition to the technical aspects, there are temporal, social, and organizational aspects of the problem-solving process, no less important in many cases; we will discuss these aspects in a later section.

Figure 7 tries to align the metacognitive skills relevant to monitoring and controlling the technical process of problem solving. In its present evolution, the conceptual model of technical skills identifies seven major capabilities:

- detecting problems
- representing problems
- planning strategies for solving problems
- applying the selected problem-solving method
- implementing the solution
- monitoring the solution
- evaluating the solution

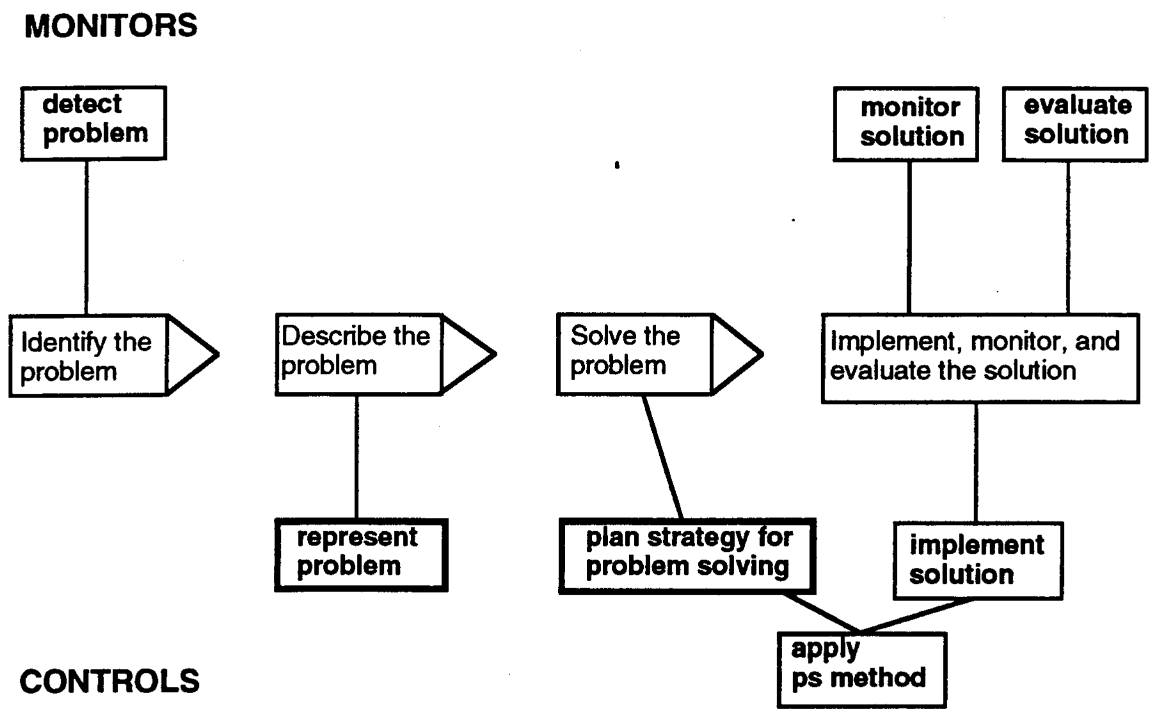



*Figure 7.* A model of metacognitive skills influencing technical problem solving.

Of these seven metacognitive skills, strategy planning is the most complex, as broken down into more detail in Figure 8. Among the metacognitive skills involved in planning, effective and efficient allocation *of resources* is one that seems to be required at several points in the problem-solving process. A military commander, for example, will allocate the G2 staff to intelligence gathering and assessment, while the G3 staff begins the application of the problem-solving method (in this case, the method of the Command Estimate). The planner must also determine the most effective and efficient *knowledge-acquisition technique,* matching the knowledge characteristics of the problem domain with a technique for eliciting that knowledge from a particular source (Geiwitz, Kornell, & McCloskey, 1991). The technique must then be applied properly to *gather information.*

Once situation assessment has proceeded to the point of *identifying the particular kind of problem* being considered, *a problem-solving method is selected* with skills similar to those in selecting the knowledge-acquisition technique, matching the method to the problem type (Bylander & Chandrasekaran, 1988). Two common problem types are shown in Figure 8: "Caused" problems are the type for which the Kepner-Tregoe methods are appropriate, that is, something is causing a problem for a business, and the identification of the cause is accomplished by comparing similar situations with and without problems. Problems with multiple solutions include the problems faced by mission planners, who use the general method of generating several options (COAs) to be evaluated.

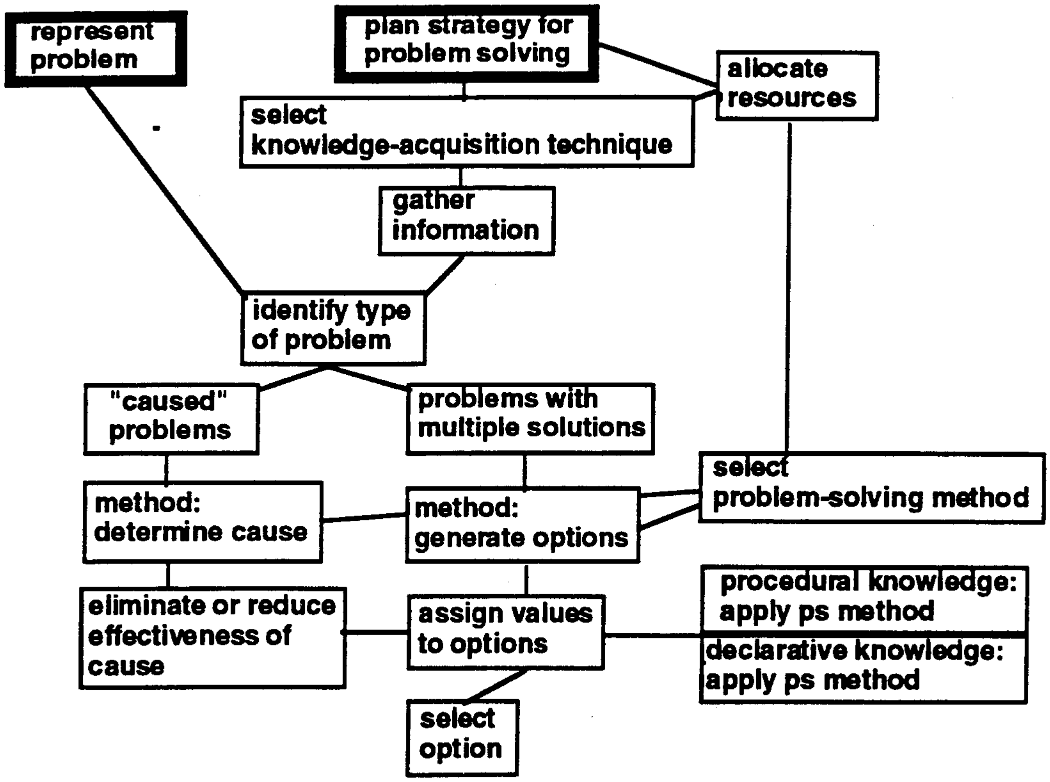



*Figure 8.* Expansion of the model for the metacognitive skills abstracted as Problem Representation and Problem Solving.

The *application of the problem-solving method* selected, as in the performance of any task, requires both task knowledge (declarative knowledge) and task skills (procedural knowledge). Similarly, the performance of the final three tasks in the problem-solving sequence — *implementation, monitoring, and evaluation of the solution* — requires both procedural and declarative knowledge, in the sense that Reif and Larkin's physics students needed to know not only the physics principle to be applied to a problem but also how to apply it (procedural knowledge). Figure 9 depicts these last three skills, and we must add *allocation of resources*, in this case for the implementation phase. For example, a military commander makes an array of forces in his mission planning and also allocates other resources such as helicopters and artillery.

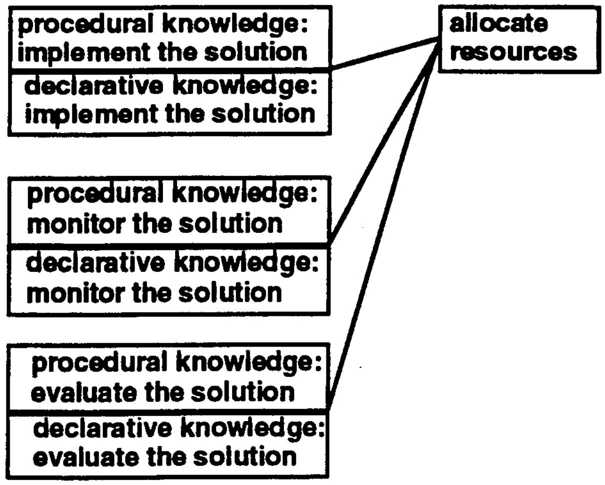



*Figure 9.* Metacognitive skills in implementation, monitoring, and evaluation.

## TEMPORAL, SOCIAL, AND ORGANIZATIONAL MONITORING AND CONTROL

Technical skills, cognitive or metacognitive, are better conceptualized than temporal, social, and organizational skills, although the latter are of critical importance in the assessment and training of executive performance. What we present in this section is by no means an adequate model of these nontechnical skills, but rather a scaffolding for the later construction of such a model. We have some comments on what these models might look like, at the end of this section.

**Temporal skills.** As defined previously, temporal skills have to do with the effective use of time in problem solving. *Scheduling* is one such skill, one that enables the executive to allocate temporal resources effectively to complete the task in the allotted time. For example, the Army has developed the "1/3, 2/3 rule" for mission planning, that is, a commander at any echelon should use 1/3 of the total time before the beginning of mission execution for his planning and leave 2/3 for subordinate commanders to do their planning. Another important temporal skill is *synchronization* (Long, 1989). In Army practice, tactical commanders are taught to construct a synchronization matrix (Tactical Commanders Development Course at Fort Leavenworth), in which the temporal aspects of the actions (start, stop, etc.) of each of the seven Battlefield Operating Systems (BOS) are charted, to ensure maximum impact of the operation as a whole. In most complex problem solving, several resources must be synchronized.

**Social skills.** Effective leaders allocate human resources wisely and delegate responsibility in a way that satisfies the technical, temporal, and organizational requirements of the task. Studies of leaderless groups show that two types of leaders typically emerge: a task leader, who facilitates the technical aspects of problem solving in a group, and a socioemotional leader, who facilitates the social aspects. There are several social skills relevant to problem solving. One is the ability to *motivate* subordinates and to use rewards (and possibly punishments) effectively. Laskey et al. (1990) speak of the importance of shared ownership, that is, an effective leader takes all points of view into account and develops a consensus in which all

participants consider themselves to have contributed to. *Conflict management* is another important social skill.

**Organizational skills.** In a previous section, we referred to organizational skills as executive monitoring. Executives have key positions in a hierarchical network and, to be effective, must understand their position and its relationship with superordinates, subordinates, and peers. Executives must know the long-term goals of the organization and how such goals are achieved in the context of the organizational structure. In the business world, this skill is often described as "seeing the big picture" (Carducci, 1993). The big picture includes an understanding of how the department in which one works, say R&D, fits with other divisions of the company, such as marketing, sales, planning, accounting, etc.

Executives are especially skilled at organizational development, which in the case of business organizations means business development; in the Army, organizational development means the creation, equipping, training, and fielding of military units, while exploring new technologies, training methodologies, and other innovations that might lead to more effective armies in the future.

**The conceptual model.** Temporal, social, and organizational skills are clearly important to effective executive performance, but they have rarely been modeled. Even more rarely have these metacognitive skills been modeled in the same context as technical problem-solving skills. One possibility, which we will explore, is a generic model like the one presented in Figure 4 for technical problem solving. Perhaps the same model can be used for the four different sets of metacognitive skills: technical, temporal, social, and organizational. For temporal skills, the problems would most likely have a time line — "We are going to run out of ammunition around 1600 hours." The solutions would also be time-based; in many cases, they would be scheduling solutions or synchronization solutions. Allocation of resources over time would also contribute to the solutions.

Similarly, the social skills would aid in the solution of social problems that are preventing the executive from reaching organizational goals. The technical problem may have been solved, but the executive's subordinates are reluctant to execute the solution because of fear or fatigue. The social solutions would be of the sort that reduce conflict in the group and motivate the group members to work toward the group's goals. Organizational skills would aid in the solution of organizational problems, e.g., if the organizational structure is such that no one has responsibility for certain subtasks, an organizational solution might assign such responsibility in an ad hoc fashion, to facilitate goal attainment. I am reminded of my boss on a road crew I once worked for: Working long hours in the hot summer, the workers complained of boredom and lack of motivation; they proposed that jobs be rotated, so that one day I might clean the road in advance of the seal-coating unit, the next day I might drive a packer, and the third day I might drive a gravel truck. A social motivational problem. The boss said, however, that the proposed solution could not be implemented because of a conflicting organizational problem that would arise if it were: No one worker would have responsibility for the maintenance of his piece of equipment, which we had to admit meant that the equipment would surely fall into disrepair.

## TRAINING AND ASSESSMENT

The purpose of the conceptual model is to guide training and assessment of metacognitive skills in executive-level commanders. To do so, the model must include training and assessment agents and objects derived from and related to the model of the metacognitively influenced task; the model must have training and assessment modules. This section will suggest possible answers to the questions of how we can train metacognitive skills and how we can assess them in experienced commanders.

We are wandering into uncharted territory here, with only a few good pioneers to guide us. I warn you of this, to warn you that you will see less careful documentation of my ideas from here on in. We are in an early stage of science, one characterized by "mucking around" in the domain, as one philosopher once termed it, getting our feet wet, glad to see any solid stands of ground.

### TRAINING

Most of the psychological research on metacognition has heretofore been developmental, focused on childhood changes with age and experience. This research gives some clues as to the ways such skills can be trained, but unfortunately the focus has been on when (at what age) such skills develop and what effect such skills have on children's performance (enhanced) in intellectual tasks. Case (1984), for example, describes ten levels of intellectual skill development, the last three or four of which are skills involving abstractions similar to the metacognitive processes described in the conceptual model. These skills presumably develop in the teens, with the ability to do "abstract mapping" observed in most cases between 14 and 16 years. Case says little about how these skills develop — some may require neurological development. Case does hypothesize that the limited processing capacity of humans is first devoted to basic operations and then, as these (cognitive) skills develop and require less conscious control, more of the capacity can be devoted to metacognitive, support skills. Sternberg (1984) has similar ideas, describing a process in which crude metacognitive skills (metacomponents) are used to control intellectual operations, receive and interpret feedback on the results of such operations, and refine themselves on the basis of that feedback. In Sternberg's theory, "the metacomponents form the major basis for the development of intelligence" through continual feedback loops (Sternberg, 1984, p. 172). If the metacomponents are not used to increase metacognitive skills, significant increases in intellectual performance are unlikely; mere experience or practice will not be effective.

Metacognitive skills support problem solving performance in abstract ways, providing a general framework and a general procedure. Thus, the problem solving methods described by Kepner and Tregoe (1965) and Plunkett and Hale (1982) can be taught as metacognitive skills. In such training programs, students are taught how to detect, define, and describe the problem, and then how to identify and eliminate the cause of the problem. These training programs, in a sense, teach the scientific method for problem solving.

The science training program of Reif and Larkin adds the substance to the promise. Reif and Larkin have, in effect, trained metacognitive skills in problem

solving for the domain of academic physics courses, with astounding success. We will borrow heavily from Reif and Larkin in our training program design. We need only apply the techniques to a new domain, Army command and control.

It is important to stress the recurring note in these investigations: **Unless one teaches the procedural knowledge, the semantic knowledge will be useless.** It is imperative to tell your students how to do it, that is, the nitty gritty, the hands-on, no holds barred, this is step one, this is step two, etc.

Can one train people to use abstract, domain-independent inferential rules to think about important events in their lives? A surprising number of theorists say no, that Plato's doctrine of formal discipline, which holds that the study of abstract rule systems trains the mind for reasoning about concrete problems, is invalid (Thorndike, 1906). Thorndike was able to show that there was very little transfer of training from one course of study (e.g., Latin) to other courses. If his view is correct, we will have little luck training metacognitive skills. But current work on this issue, exemplified by the research of Nisbett and his colleagues (Nisbett et al., 1987), suggests that abstract skills can be taught. The primary problem in the transfer of training is in the ability of students to apply the abstract rules to specific domain content. This, the proper representation of the problem so that the abstract rule can be seen to apply, is what needs to be taught.

Specific metacognitive skills have been the substance of specific training courses, and experience of this sort also illuminates our approach to training metacognitive skills in general. For example, synchronization of resources has been trained at Fort Leavenworth for several years, in a precommand course called Tactical Commander's Development Course (TCDC). Students are taught a general methodology that can be applied to specific mission-planning exercises (Long, 1989). In essence, they are given a matrix to plan the activities of each of the seven Battle Operating Systems (BOSs) along a time line that begins before H-hour and continues into sequel missions. They are given extensive practice filling in the matrix in a variety of mission-planning exercises and encouraged to continue the practice in their command roles. Synchronization is a metacognitive skill related to temporal monitoring.

Social monitoring and control comprises a set of metacognitive skills related to team or group performance. Salas and his colleagues have been developing theory concerned with the training of teamwork skills, which has obvious implications for training metacognitive skills (e.g., Glickman et al., 1987). Findings include the fact that, for most team training, training in a team context is superior to individual training on team tasks. Also, three distinct factors appear in team training: a taskwork factor, reflecting training on the team task; a teamwork factor, reflecting learning to coordinate and communicate within the team; and a jelling factor, which reflects the ability to put the taskwork and the teamwork together in an integrated approach to problem solving in the group setting. These three factors are distinct at the beginning of training, but converge during the final stages of training. These findings bear a striking resemblance to the concept of two kinds of leadership: task leadership and socioemotional leadership.

## ASSESSMENT

The first step in skill assessment is a thorough task analysis, according to the standard Instructional Systems Development (ISD) methodology (Vineberg & Joyner, 1980). If the goal is to assess a cognitive skill, one must do a cognitive task analysis. Our goal is to assess a metacognitive skill; what then is required of us? A metacognitive task analysis? Procedural or behavioral task analysis is a fairly well-defined technique (Drury et al., 1987), and even cognitive task analysis is becoming more common and more standardized (Lesgold et al., 1990). Methods for group cognitive task analysis have been developed (Salas, 1993). But I know of no work on individual or group metacognitive task analysis. Before we can begin to construct tests of metacognitive skills, we must first develop such a task-analysis methodology. The *training* of metacognitive skills also depends on such analyses.

Once the appropriate task analysis has been accomplished, the knowledge and skills (KSs) required to perform each step are determined. The KSs (not the procedural steps of the task) are the "raw material" of both training programs and assessment devices. Classroom training is designed to provide the task knowledge, whereas laboratory and on-the-job training is designed to teach task skills. Verbal tests are designed to assess task knowledge and performance tests are designed to assess task skills. So the question before us is, How do we assess metacognitive skills and knowledge related to problem solving?

Cognitive task analysis uses knowledge-acquisition techniques (KATs) to elicit the knowledge and the covert decision processes involved in cognitive task performance (Geiwitz, Kornell, & M'Closkey, 1992). Many KATs also seem appropriate for the investigation of metacognitive KSs. Protocol Analysis, for example, has a domain expert "think out loud" while performing the task (Ericsson & Simon, 1984). If the expert were primed, not to describe the direct problem-solving processes, but to describe the goals of the endeavor and the strategy for goal attainment, we might elicit the metacognitive steps that monitor and control the direct processes. These steps could then be analyzed for required KSs in a conventional manner. Similarly, since effective problem representation is a key metacognitive skill, we could use the KAT called Cognitive Structure Analysis (Leddo & Cohen, 1988). (This technique grows from a conceptual model called Integrated Knowledge Structures — INKS — described by Laskey et al., 1990.) Cognitive Structure Analysis purports to identify the knowledge representations the expert uses: production rules, scripts, frames, semantic networks, or mental models. Not only would this KAT be useful in identifying the expert's representation of the problem, it might also describe the expert's overarching representation of the problem-solving process. I suspect that most scientists have a mental model of the scientific method that they use for the everyday conduct of scientific activity.

Several metacognitive skills are the subject of psychological research, and the criterion variables used to represent these skills may provide a means of assessment. Aircrew coordination and communication, for example, has been operationalized as ratings based on specific behaviors, e.g., the discussion of potential coordination problems during preflight briefings (Franz et al., 1990). Performance in games or simulations has also been used to define metacognitive skills. These games require

coordination between two or more team members for superior performance (Bowers et al., 1992).

Finally, there are numerous tests available for the assessment of reasoning and problem solving ability. Tests of diagnostic ability (e.g., troubleshooting) are also available.

We should mention a special assessment technique known as Career Path Appreciation (CPA; Stamp, 1988). CPA was developed to measure the level of cognitive complexity that a member of an organization was dealing with at the present time. This level is assumed to predict later career development according to Stratified Systems Theory (Jacobs & Jaques, 1987). CPA is essentially a structured interview that focuses on a respondent's general approach to problems; it should therefore be well adapted for the assessment of metacognitive skills. However, very little information is available on the technique or on the scoring of the interview protocols.

## TRAINING METACOGNITIVE SKILLS

Table 2 aligns the ten metacognitive skills with the procedural steps for mission planning known as the Command Estimate. The tables following describe in outline form the nature of the training to be developed in the Army domain.

TABLE 2

## STEPS IN THE COMMAND ESTIMATE AND CORRESPONDING METACOGNITIVE SKILLS

| THE COMMAND ESTIMATE | METACOGNITIVE SKILLS |
|---|---|
| Receive Mission | Detect Problem |
| Analyze Mission | Represent Problem |
| Restate Mission | Represent Problem |
| CDR's Guidance | Plan Strategy for Problem Solving |
| Develop COAs | Apply Problem-Solving Method |
| Analyze COAs | Apply Problem-Solving Method |
| Recommend COA | Describe Solution |
| Select COA | Describe Solution |
| Construct OPORD | Communicate Solution |

TABLE 3

## THE COMMAND ESTIMATE

**Detection of the problem: No training. Mission comes from higher unit.**

**Representation of the problem: the Intelligence Preparation of the Battlefield (IPB), very detailed, very procedural.**

**Selection of ps method: always use the same method (the command estimate process)**

**Resource allocation: very little not specified by doctrine, e.g., G2 staff responsible for IPB.**

**Strategic application of ps method: always perform the same.**

**Evaluation of solution candidates: three COAs and the decision matrix; wargaming the COAs**

**Recognition of errors: no procedures**

**Temporal monitoring: synchronization matrix**

**Social monitoring: trained as teams**

**Organizational monitoring: the military's big advantage; everyone knows the command structure and how it works**

TABLE 4

## SPECIFIC DEFICIENCIES IN THE COMMAND ESTIMATE

**Representation of the problem in terms of goals: Planners must know the commander's intent two levels up, but make no real use of this information.**

**Commander's Guidance: no real use now. cdrs often say nothing, to see what their staff can come up with. then they say, none of these, this instead. staff feels like mushrooms, kept in dark and fed shit. Will train cdrs to identify "Dangers and Opportunities" in the situation, tell staff to worry about dangers, exploit opportunities.**

**Problem-solving method: is one sufficient? decision matrix needs work, e.g., no weighting of factors.**

**Selection of COA: If cdr does not go with staff recommendation, then the COA chosen is never evaluated. Also true if a combination of COAs is chosen.**

TABLE 5

## TRAINING METACOGNITIVE SKILLS IN THE COMMAND ESTIMATE

**Current training already trains several metacognitive skills to aid several of the steps. Need to highlight metacognitive aspects, provide more declarative knowledge, and ensure that the procedural knowledge is experienced and practiced.**

**ISD methodology: Thorough task analysis and appropriate knowledge acquisition --> knowledge and skills for task performance --> metacog knowledge and skills for superior task performance.**

**Teach metacog knowledge in lectures, train metacog skills in laboratory exercises. Provide lecture notes and overheads. Provide procedures and worksheets for laboratory exercises, with quizzes.**

**Assess metacog knowledge thru verbal (multiple choice) tests; assess metacog skills thru objective performance tests.**

TABLE 6

# TRAINING: PROBLEM DETECTION

| <u>**COMMAND ESTIMATE**</u> | **METACOGNITIVE** <u>**SKILLS OR KNOWLEDGE**</u> |
|---|---|
| RECEIVE MISSION | PROBLEM DETECTION |
| basic question | How do you know a problem exists? |
| declarative knowledge | --compare current state to goal state, discrepancy indicates problem<br>--military situation: problem detection = reception of orders |
| procedural knowledge | --represent problem in current state, use same representation for goal state; note discrepancies for goals and subgoals |

TABLE 7

## TRAINING:
## PROBLEM REPRESENTATION

| COMMAND ESTIMATE | METACOGNITIVE SKILLS OR KNOWLEDGE |
|---|---|
| ANALYZE MISSION, RESTATE MISSION | PROBLEM REPRESENTATION |
| basic question | How should the problem be described? |
| declarative knowledge | --goals most important, must be stated explicitly, for the unit and for two levels up (commander's intent)<br>--importance: a) sets the goal state; b) if cut off, can continue mission<br>--represent problem in terms of battlefield objects, including terrain, and the forces on each object (size and strength of units, friendly and enemy) |
| procedural knowledge | --determine facts and assumptions<br>--G2 applies IPB<br>--mission analysis (goals + specified & implied tasks)<br>--constraints & restrictions<br>--time analysis<br>--develop SitMap using military symbols<br>--overlays (COO, situation, event, decision support) |

TABLE 8

# TRAINING: COMMANDER'S GUIDANCE

| **<u>COMMAND ESTIMATE</u>** | **METACOGNITIVE <u>SKILLS OR KNOWLEDGE</u>** |
|---|---|
| COMMANDER'S GUIDANCE | PLAN STRATEGY FOR PROBLEM SOLVING |
| basic question | How should the planners proceed? |
| declarative knowledge | --*Dangers* are aspects of the situation that present planning difficulties;<br>-- *Opportunities* are aspects of the situation in which the relative advantage falls to us<br>--combat power ratios: 1:3 for defense, 3:1 for attack |
| procedural knowledge | --present mission and restated mission<br>--incorporate time factors<br>--state acceptable risk<br>--Dangers & Opportunities |

TABLE 9

# TRAINING: DEVELOP COAS

| COMMAND ESTIMATE | METACOGNITIVE SKILLS OR KNOWLEDGE |
|---|---|
| DEVELOP COURSES OF ACTION | APPLY PROBLEM-SOLVING METHOD |
| basic question | What are the best courses of action? (usually best three) |
| declarative knowledge | --goals and tasks from the restated mission<br>--combat power ratios<br>--maneuver schemes<br>--command & control requirements |
| procedural knowledge | 1. analyze relative combat power<br>2. array initial forces<br>3. develop scheme of maneuver<br>4. determine C2, control measures<br>5. prepare COA statements & sketches |

TABLE 10

## TRAINING: ANALYZE COAS

| <u>COMMAND ESTIMATE</u> | METACOGNITIVE <u>SKILLS OR KNOWLEDGE</u> |
|---|---|
| EVALUATE COURSES OF ACTION | APPLY PROBLEM-SOLVING METHOD |
| basic question | Which of the 3 COAs is best? |
| declarative knowledge | --wargaming theory, including enemy doctrine (G2)<br>--criteria for decision matrix<br>--criteria weights<br>--7 BOSs analyzed<br>--G1, G4 wargame too |
| procedural knowledge | --wargaming procedure<br>--decision matrix<br>--temporal monitoring: synchronization matrix |

TABLE 11

# TRAINING: RECOMMEND, CHOOSE, COMMUNICATE COAS

| <u>COMMAND ESTIMATE</u> | **METACOGNITIVE <u>SKILLS OR KNOWLEDGE</u>** |
|---|---|
| RECOMMEND, CHOOSE, COMMUNICATE COA | APPLY PROBLEM-SOLVING METHOD; DESCRIBE SOLUTION; COMMUNICATE SOLUTION |
| basic question | Which COA should we follow? |
| declarative knowledge | --decision matrix<br>--Army orders formats<br>--command & control requirements |
| procedural knowledge | --evaluate solution (ala Reif)<br>--make decision<br>--describe in terms of problem<br>--describe in terms of orders formats |

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## APPENDIX A

## INSTRUCTIONS FOR PROBLEM DESCRIPTION

The following are detailed instructions for effective problem description, used in Heller and Reif (1984). Two models are included: M is the metacognitive skill model, and M* is the conventional model for description taught in most physics textbooks. Instruction not specifically marked are common to both models. E=experimenter, S=subject.

*Theoretical Description of Systems*

M [ E: "Let's now draw diagrams describing each system of interest."

M* [ E: "Let's now draw diagrams describing the forces on each system of interest."

*Choice of Particular System*

E: "Which system . . .do you wish to consider (first)/(next)?" (1)

S: Names a system *'X'*.

*If X* is a string or is not affected by interactions with other systems:

E: "There is no need to describe *X*." (2)
Return to step 1.

*Else* continue:

M only [

*Motion Description*

E: "First draw a motion diagram of *X*, including any available information about its position, velocity, and acceleration relative to a convenient reference frame. If the velocity or acceleration is zero, indicate that on your diagram." (3)

S: Draws motion diagram of *X*.

E: "It is also useful to include on this diagram any known properties of the system, such as mass." (4)

*If* previous systems have been described:

E: "Be sure to use convenient symbols and to relate them to those you've used previously." (5)

*If X* has circular motion:

E: "Remember, the acceleration of a system in circular motion ordinarily, although not always, has two components, one tangential and the other toward the center of the circle. Check to be sure whether both components exist in this case." (6)

]

*Interaction Description*

E: "Now let's draw an interaction diagram for $X$, using the method I've suggested."

*Short-Range Forces*

M

E: "First name each system that touches $X$, including those that exert applied forces. As you identify each system, indicate all external contact forces exerted on $X$ by that system." (7)

M*

E: "Draw a force diagram indicating the forces exerted on $X$ by all other systems." (7′)

*If* previous systems have been described:

E: "Be sure to use convenient symbols and to relate them to those you've used previously." (8)

S: Names interacting systems ('$Y$') and/or indicates forces.

M only

*If* interaction with surface:

E: "Remember, the force exerted by a surface ordinarily, although not always, has two components, the normal force and friction force. Check to be sure whether both components exist in this case. (9)

The normal force is perpendicular to the surface and directed away from it. The friction force opposes the *relative* motion of the contact points—here it opposes the motion of $X$ relative to $Y$." (10)

*Long-Range Forces*

E: "Name all external systems that directly interact with $X$ without touching it or through any other physical contact. Then indicate the long-range forces exerted on $X$ by each such system." (11)

S: Names system and/or indicates force.

*Check: Missing or Extraneous Forces*

M

E: "Are there any other systems touching $X$?" (12)

M*

E: "Are there any other forces on $X$ by anything else? (12′)

S: "Yes" or "no".

*If* yes:

M E: "Draw the forces exerted by that (those) system(s)." (13)

M* E: "Draw the forces." (13′)
Return to step 12.

M only *Else* continue:

E: "Are there any other systems directly interacting with $X$ by long-range forces?" (14)

S: "Yes" or "no".

*If* yes:

E: "Draw the force exerted by that system." (15)
Return to step 14.

*Else* continue:

E: "If not, you are finished describing all forces on $X$. Do not add any others. (16)

*Check: Consistency Between Motion and Interaction*

E: "The motion and interaction of the system must be consistent. In your diagrams, are the forces on $X$ such that, with proper magnitudes, their vector sum can have the same direction as $X$'s acceleration? Show me how you determine this. (You might want to check whether this is true by comparing components along convenient directions.)" (17)

S: Checks consistency; responds "yes" or "no" with explanation. Modifies description(s) if necessary.

E: "What would have to be true about the relative magnitudes of the forces on $X$ for the acceleration and resultant force to have the same direction?" (18)

S: Describes required relative magnitudes of forces.

*Repetition of Description for Each System*

E: "Have all systems of interest been described yet?" (19)

S: "Yes" or "no".

*If* no:

Repeat theoretical description procedure, beginning at step 1. (20)

*Else* continue:

*Check of Entire Description*

E: "After describing all systems, it's useful to double-check your work. Let's run through a checklist to make sure you haven't missed anything."

*Check: Choice of Useful Symbols*

E: "All arrows should be labeled." (21)

S: Checks arrows.

E: "Except for the gravitational force (which may be expressed as "mg"), or any magnitudes actually given in the problem statement, the values of quantities should *not* be evaluated at this time. Symbols like "F," "T," and "N," with subscripts, should be used instead." (22)

S: Checks symbols.

E: "Look at the symbols in all of your diagrams. Wherever different symbols have been used, the values of these quantities should *actually* be unrelated. If values are the same or simple multiples, use the same symbol. If values are unrelated, different symbols should be used." (23)

S: Checks symbols.

*Check: Use of all Information in Problem*

E: "All information specified in the problem should be incorporated in your analysis. Please reread the problem carefully to make sure you have considered all the given information. In particular, make sure you've obtained from the problem all available information about the magnitude and direction of the velocity and acceleration of each system." (24)

S: Rereads problem statement. Modifies descriptions if needed.

*Check: Exploitation of Constraints (Mutual Forces)*

M only

E: "Check to make sure that all action-reaction pairs of forces are described as equal in magnitude and opposite in direction. For example, if systems *A* and *B* interact, the force of *A* on *B* in your diagram of *B* should be opposite in direction but should have the same magnitude as the force of *B* on *A* in your diagram of *A*. Look for forces between each pair of systems and check that they are described right." (25)

S: Checks forces.